

**FUNDAMENTAL STUDIES OF NEURAL STIMULATING ELECTRODES**

**Tenth Quarterly Report  
Covering Period November 29, 1996 to February 28, 1997**

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## 1. INTRODUCTION AND SUMMARY

This report describes work on NINDS Contract No. N01-NS-4-2310 during the period November 29, 1996 to February 28, 1997. As part of the Neural Prosthesis Program, the broad objectives of the present fundamental studies are: 1) to evaluate the electrochemical processes that occur at the electrode-electrolyte interface during pulsing regimens characteristic of neural prosthetic applications; 2) to establish charge injection limits of stimulation electrode materials which avoid irreversible electrochemical reactions; 3) to develop an *in vitro* method, which can be applied *in vivo*, for determining the electrochemical real area and stability of microelectrodes; 4) to develop new materials which can operate at high stimulation charge densities for microstimulation; and 5) to provide electrochemical and analytical support for other research activities in the Neural Prosthesis Program at NINDS.

During this reporting period, long term studies of U. Michigan ribbon-cable-probe No. 1, site 1, were continued. The apparent capacitance of the unactivated site, calculated from the current at 0.0 V vs. Ag/AgCl in a 200 V/s potential sweep, has been monitored for over 524 days of soaking in PBS. An abrupt but modest increase in the capacitance from 0.5 nF to ~2.5 nF was observed at day 91 of the soak test. On day 217, the electrode was inadvertently allowed to dry out. After the electrode was rehydrated, the apparent capacitance had decreased to a value closer to that observed before day 91. There has been no increase in  $C_{app}$ , similar to that observed at day 91, for the 307 days of soaking since the electrode was rehydrated at day 217.

The affect of activation potential limits, pulse duration and electrolyte pH on the uniformity and growth rate of AIROF has been evaluated. Our previous studies (see QPR Nos. 8 and 9) suggest that uniform activation can be achieved with potential pulse activation provided the dwell time at each potential limit is long enough for the activation current to reach background levels. A dwell time of 10 s, compared with the more typical value of 0.5 s, appears effective in providing uniform activation of large area (~0.1 mm<sup>2</sup>) electrodes. Cathodic and anodic potential limits of -0.7 and +1.0 V vs Ag/AgCl resulted in the highest AIROF activation rates in 0.1 M PBS. Comparable anodic and cathodic potential limits in 0.3 Na<sub>2</sub>HPO<sub>4</sub>, -0.80 and +0.90 V, resulted in a higher AIROF activation rate than that in PBS.

## 2. VOLTAMMETRIC STUDIES ON Ir MICROELECTRODES

During this quarter we continued studies of the long term stability of Ir sites on a probe with an integrated ribbon cable received from U. Michigan. Figure 2.1 is a diagrammatic representation of the probe showing the numbering scheme for the electrode sites. The probe has been under soak in phosphate buffered saline (PBS) for 524 days.

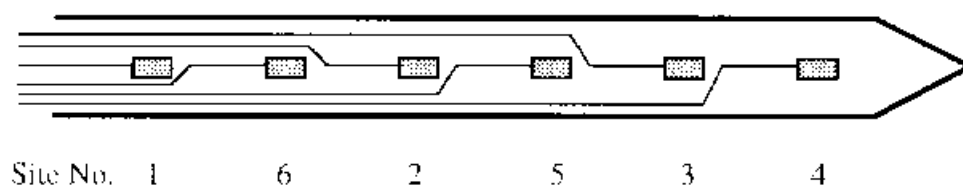


Figure 2.1 Diagrammatic representation of sites and site identification on U. Michigan ribbon-cable probe.

Measurements of the apparent capacitance of site 1 of the ribbon-cable-probe No. 1 were continued. Test procedures and results are detailed in previous Quarterly Progress Reports (Nos. 5-9). The apparent capacitance,  $C_{app}$ , at 200 V/s, is plotted in Fig. 2-2 as a function of time for the three studies performed this quarter along with data from the 25 studies conducted during the previous five quarters.  $C_{app}$  is calculated by dividing the current at 0.0 V vs. Ag/AgCl by the scan rate, thus  $C_{app} = Q/V = i/v$ , where  $v$  is the scan rate.

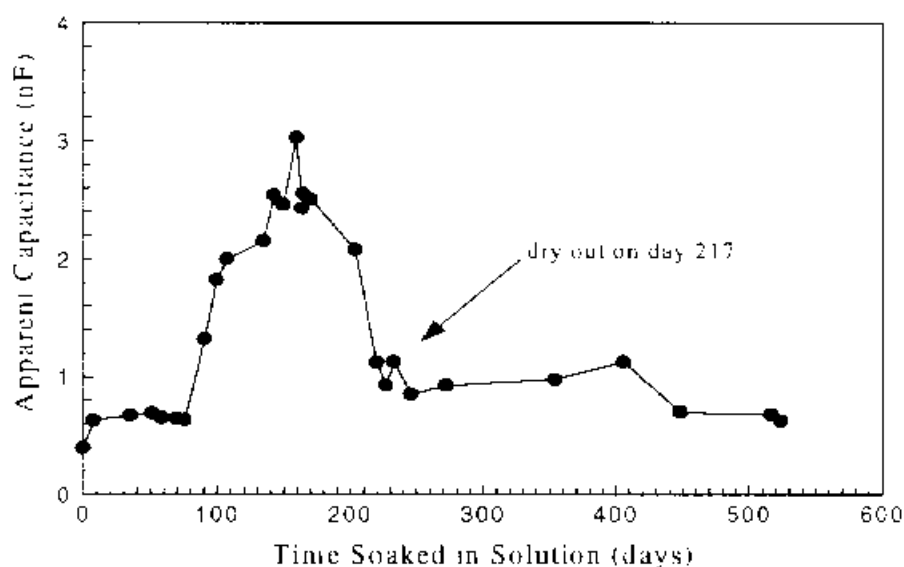


Figure 2-2 Apparent capacitance of site 1 on U. Michigan ribbon-cable probe No. 1 at 200 V/s for the 28 scan rate studies.

We do not have a satisfactory explanation for the increase in apparent capacitance between days 91 and 220. The inadvertent drying out of the electrode at day 217 presumably caused the decrease in  $C_{app}$ . However, there has been no increase in  $C_{app}$  similar to that observed at day 91 for the 307 days of soaking since the electrode was rehydrated at day 217. This result, and the abruptness of the increase observed at day 91, suggests that the increase in  $C_{app}$  is not due to an ongoing degradation process at the electrode site. A comparison of the voltammetric scans used in the calculation of  $C_{app}$  at 200 V/s for days 59, 160, 354 and 517 is shown in Fig. 2-3. The 59, 354 and 517 day scans are not significantly different with only a modest increase in current observed for the longer soaking times. This difference might be due to an increase in the surface area of Ir accessible to the electrolyte or the formation of iridium oxide due to prior electrochemical testing at expanded limits. In either case, some increase in  $C_{app}$  via either mechanism is anticipated and, overall, this site has exhibited a stable electrochemical response for more than one year of soaking in 0.1 M PBS.

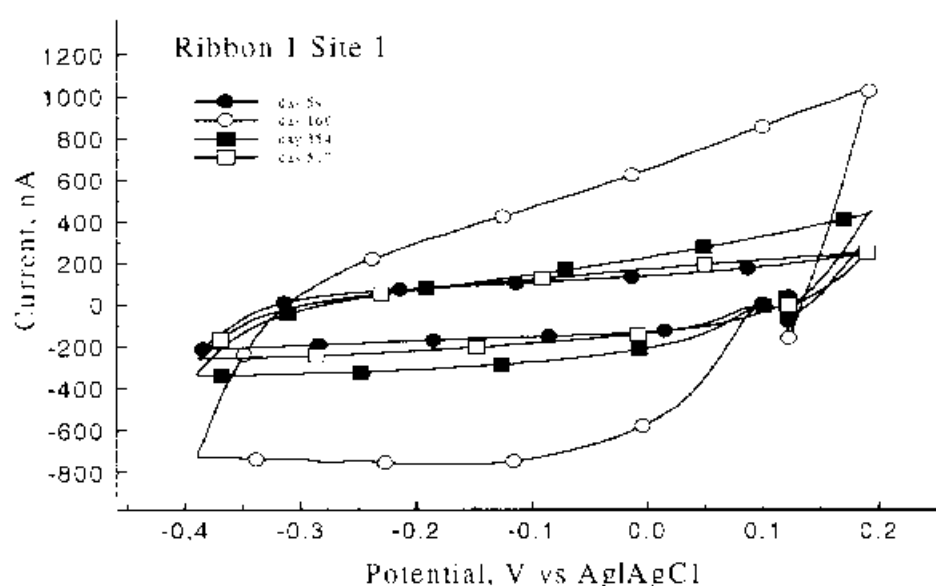


Figure 2-3 Voltammetric scans of site 1 on U. Michigan ribbon cable probe No.1 after 59, 160, 354 and 517 days of soaking. Scan rate = 0.05 V/sec.

### 3. IRIIDIUM ACTIVATION STUDIES

#### 3.1. Experimental Setup for Activation

The electrolytes used for activation and evaluation of AIROF are the following: phosphate-buffered saline (PBS), 0.08 M  $\text{Na}_2\text{HPO}_4$  0.02 M  $\text{NaH}_2\text{PO}_4$ , and 0.12 M NaCl at pH 7.2; and 0.3 M  $\text{Na}_2\text{HPO}_4$  at pH 9.1. These electrolytes are generally deoxygenated by a flow of Ar gas. Potentials are measured against a  $\text{Ag}|\text{AgCl}(s)|\text{Cl}^- (3M \text{ KCl})$  reference electrode (Microelectrodes Inc., No. MI-403), isolated from the electrochemical cell by a salt bridge. Two iridium electrodes were used for this portion of the activation study: a) an iridium disk (Bioanalytical Systems Inc) with nominal diameter of 127  $\mu\text{m}$  and electrochemical surface area (ESA) of  $1.4 \times 10^{-4} \text{ cm}^2$ , and b) an iridium disk fabricated at EIC by casting 1 mm diameter wire in Epon Resin 828. (ESA,  $7.89 \times 10^{-5} \text{ cm}^2$ ).

The AIROF is formed by applying consecutive sets of 50 square-wave potential pulses between fixed cathodic and anodic limits. After each set of 50 pulses, cyclic voltammograms are acquired at scan rates of 0.05 and 0.10 V/s between potential limits of -0.55 V and 0.75 V vs. Ag/AgCl for electrodes activated in PBS and -0.65 V and 0.65 V for electrodes activated in 0.3 M  $\text{Na}_2\text{HPO}_4$ . On completion of 100, 450 and 1150 pulses, additional CVs were taken at scan rates 0.005 and 0.50 V/sec, and impedance spectroscopy was performed. The anodic and cathodic charge storage capacities of the AIROF were determined by integrating the oxidation and reduction currents, respectively, during acquisition of the voltammograms. The unactivated Ir metal background was subtracted from the AIROF CVs before integration. An activation pulse width of 10 s was evaluated with various cathodic and anodic potential limits ranging between -0.35 to -0.8 V and 0.4 to 1.05 V, respectively.

#### 3.2. Influence of Activation Potential Limits and pH On Charge Capacity

In the previous quarter, a comparison of activation rate in 0.3 M  $\text{Na}_2\text{HPO}_4$  and PBS was made using standard potential pulse activation conditions between -0.6 V and +0.8 V in PBS and -0.7 V and +0.7 V in 0.3 M  $\text{Na}_2\text{HPO}_4$  with pulse widths of 10 s. The 10 s pulse width was chosen due to the linearity in the AIROF charge capacity with the number of activation pulses and the uniformity of AIROF grown under these conditions. Figures 3-1 and 3-2, taken from data presented in QPR

No. 9, show the increase in anodic and cathodic charge capacity, respectively, over an 1150 pulse activation in each electrolyte. The rate of AIROF growth is comparable in PBS and 0.3 M  $\text{Na}_2\text{HPO}_4$  up to 250, 10 s pulses, corresponding to a charge capacity of  $\sim 16 \text{ mC/cm}^2$ . With additional pulsing, the growth rate in PBS was marginally greater.

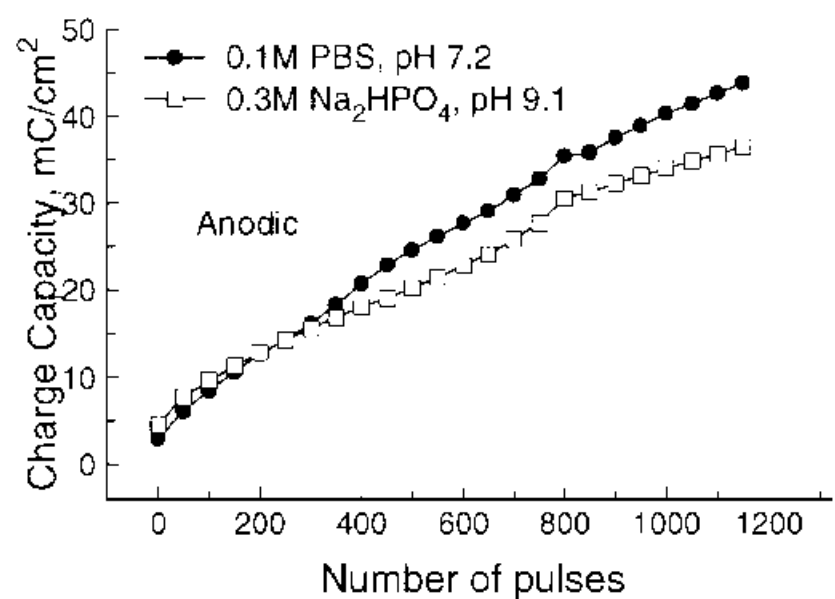


Figure 3-1. Comparison of the anodic charge capacity of AIROF activated in PBS and 0.3 M  $\text{Na}_2\text{HPO}_4$  using potential limits of  $-0.6/0.8 \text{ V}$  and  $-0.7/0.7 \text{ V}$ , respectively.

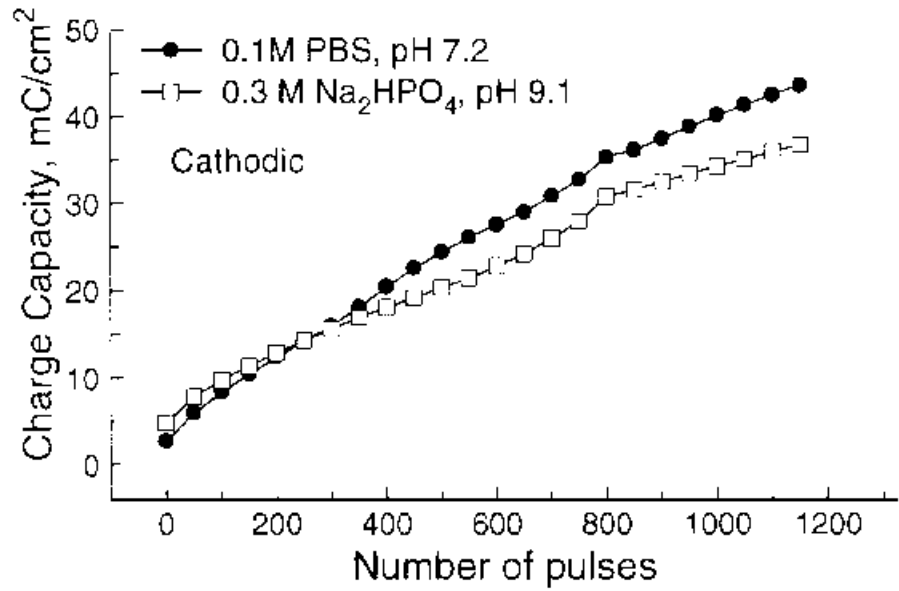


Figure 3-2. Comparison of the cathodic charge capacity of AIROF activated in PBS and 0.3 M  $\text{Na}_2\text{HPO}_4$  using potential limits of  $-0.6/0.8 \text{ V}$  and  $-0.7/0.7 \text{ V}$ , respectively.



In the following series of experiments, all in 0.3 M  $\text{Na}_2\text{HPO}_4$ , the combination of “minimum oxide growth” conditions, discussed in QPR 9, is compared to the standard activation windows as well as the combination of “maximum oxide growth” conditions. Additionally, windows slightly wider than the minimum and maximum conditions were tested. Table 3-1 lists the conditions used for potential pulse activation in 0.3 M  $\text{Na}_2\text{HPO}_4$  as well as activation limits in PBS that were discussed in previous QPRs.

Table 3-1 Potential pulse activation windows for both 0.1M PBS and 0.3 M  $\text{Na}_2\text{HPO}_4$ , minimum and maximum conditions

Experiment	Activation Window For 0.1M PBS		Activation Window For 0.3M $\text{Na}_2\text{HPO}_4$	
	Cathodic Potential Limit	Anodic Potential Limit	Cathodic Potential Limit	Anodic Potential Limit
original	-0.60	+0.80	-0.70	+0.70
original-	--	--	-0.70	+0.80
minimum	-0.45	+0.55	-0.55	+0.45
minimum+	-0.45	+0.65	-0.55	+0.55
minimum-	--	--	-0.45	+0.45
maximum	-0.70	+0.95	--	--
maximum+	-0.70	+1.00	-0.80	+0.90

As shown in Figure 3-3, the data for the cathodic charge capacity produced under minimum activation conditions (-0.55 to 0.45 V in 0.3 M  $\text{Na}_2\text{HPO}_4$ ) show a very slight increase with increasing pulse number, indicating no significant iridium oxide growth. Decreasing the “minimum” activation window by 0.1 V at the cathodic limit (-0.45 to +0.45 V), resulted in no apparent growth of oxide. Increasing the “minimum” activation window by 0.1 V at the anodic limit (-0.55 to +0.55 V), resulted in the formation of some AIROF with a CSC of  $<10 \text{ mC/cm}^2$  after 1150 pulses. Additionally, the standard (-0.7 V to 0.7 V) activation window was increased by 0.1 V at the anodic limit (-0.70 to +0.80 V). After 1150 pulses, the capacity of the -0.7/0.7 V and -0.7/0.8 V activation limit AIROFs were essentially identical and similar to previous measurements in 0.3 M  $\text{Na}_2\text{HPO}_4$  (see Figs. 3-1 and 3-2). In 0.1 M PBS, the “maximum” and maximum plus 0.1 V at the anodic limit produced virtually identical results, therefore, only the later experiment was performed in the 0.3 M  $\text{Na}_2\text{HPO}_4$  solution. However, when the activation

window in 0.3 M  $\text{Na}_2\text{HPO}_4$  was increased to -0.8/0.9 V, significantly more capacity and higher rate of oxide accumulation were observed.

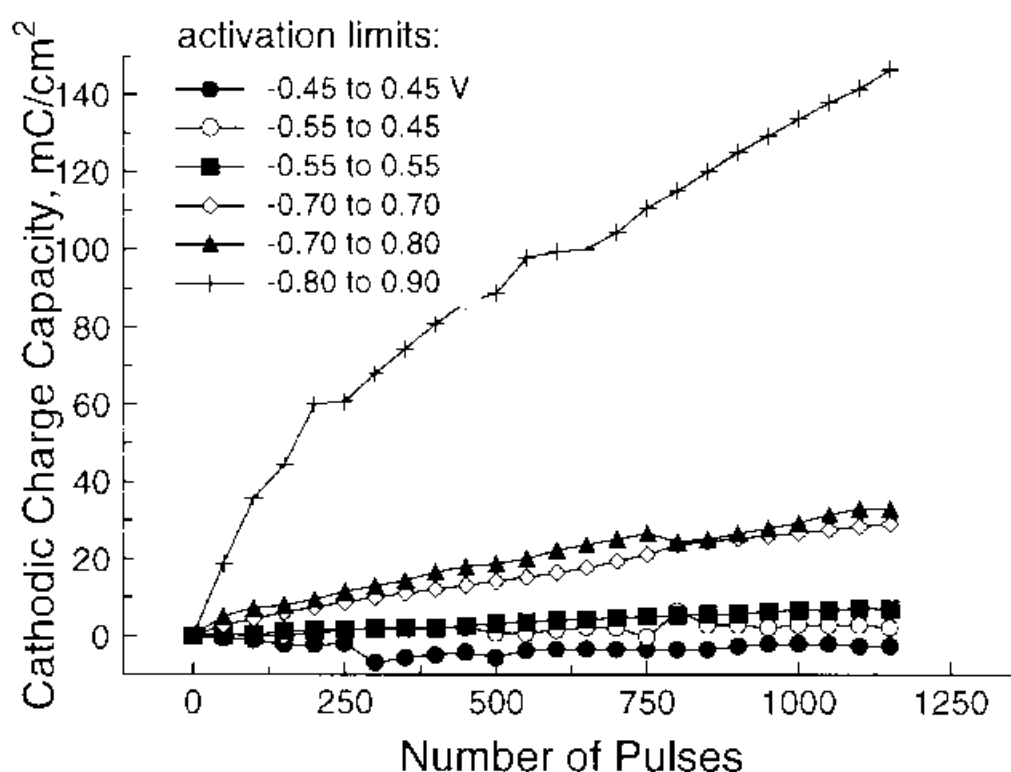


Figure 3-3 Cathodic charge capacity as a function of pulse number of AIROF activated by 10 s pulses at the potential limits indicated in 0.3 M  $\text{Na}_2\text{HPO}_4$ .

Figure 3-4 compares the "maximum+" and standard activation window cathodic charge capacities, corrected for background currents, in both electrolytes with increasing pulse number. For the standard activation windows, the rate of AIROF growth is comparable in PBS and 0.3 M  $\text{Na}_2\text{HPO}_4$  up to 250, 10 s pulses, corresponding to a charge capacity of ~10 mC/cm<sup>2</sup>. With additional pulsing, the growth rate in PBS is marginally greater. After 1150 pulses under standard conditions, the cathodic charge capacity is 37 mC/cm<sup>2</sup> and 29 mC/cm<sup>2</sup> in PBS and 0.3 M  $\text{Na}_2\text{HPO}_4$ , respectively. For the "maximum+" activation conditions, however, the growth rate in 0.3 M  $\text{Na}_2\text{HPO}_4$  is significantly greater than that for the 0.1 M PBS. The charge capacity of the AIROF activated in 0.3 M  $\text{Na}_2\text{HPO}_4$  with limits of -0.8/+0.9 V increased over the first 450 pulses to a cathodic charge capacity of ~86 mC/cm<sup>2</sup> while the AIROF activated in 0.1 M PBS with comparable limits of -0.7/+1.0 V increased to a cathodic charge capacity of 45 mC/cm<sup>2</sup>. After

1150 pulses under “maximum+” conditions, the cathodic charge capacity increases to 146 mC/cm<sup>2</sup> in phosphate compared with 77 mC/cm<sup>2</sup> in PBS.

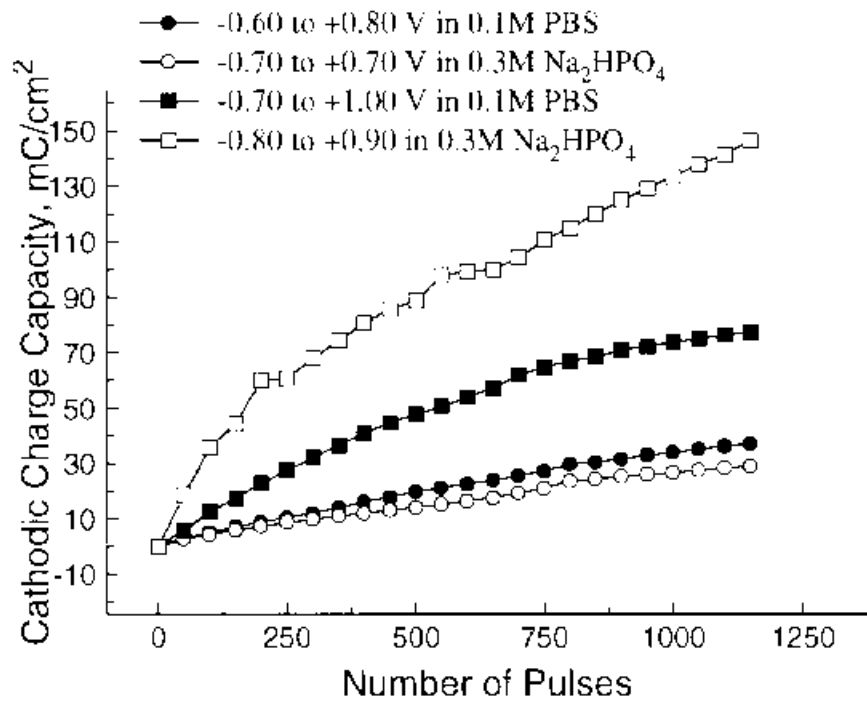


Figure 3-4 Comparison of the cathodic charge capacities for both the standard and “maximum+” activation window experiments in both PBS and sodium phosphate solutions. All data are background corrected.

The higher growth rate in 0.3 M Na<sub>2</sub>HPO<sub>4</sub> does not imply that AIROF activated in this electrolyte will have a higher stimulation charge injection capacity. A major difference in the activation electrolytes, besides pH, is the high Cl<sup>-</sup> composition in the PBS. The Cl<sup>-</sup> ion is known to adsorb on Ir, as well as other noble metals, and its presence may also affect activation rates, particularly when using more positive anodic limits. Activation experiments in pH 7.4 buffer without Cl<sup>-</sup> will be performed in the following reporting period to test the Cl<sup>-</sup> adsorption hypothesis.

#### **4. FUTURE WORK**

The evaluation of activation protocols will continue in the next quarter. The affect of activation parameters on charge injection and utilization of AIROF will be evaluated. In the previous two quarters, the use of Ti:Ir graded interface electrodes with improved stability under aggressive activation conditions was reported. During the past quarter work, an initial characterization of the response of Ti:Ir graded interface electrodes to stimulation pulsing has been completed. A more detailed analysis is planned for the upcoming quarter and preliminary data will be presented in the following QPR.